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Hypersonics Supply Chains: Securing the Path to the Future[1]

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Abstract

Over the past few years, the United States Department of Defense (DoD) has undertaken an ambitious effort to develop and deploy hypersonic technology in support of a variety of national security missions. Hypersonic weapons are maneuverable, fly at least five times the speed of sound, or Mach 5, within the Earth's atmosphere, and can deliver long-range lethal effects on short time scales. Despite this recent effort, the DoD has often wavered in its commitment to fielding hypersonic systems at scale. Some years, it has been a clear priority while other times, the commitment has been ambiguous. As such, the current supply chains, including the manufacturing base, supply of critical materials, testing infrastructure, and workforce are incapable of supporting DoD's ambitious plans. To rectify critical hypersonics supply chains vulnerabilities, a holistic and coordinated approach among government, industry, and academia is essential. This integration will facilitate the cost-effective and reliable production of operational hypersonic systems. If action is taken now, the DoD's hypersonics aspirations are within reach. The most important step the DoD can take to secure hypersonics supply chains for the future is to provide a consistent demand signal to industry.

Critical Raw Materials and Goods

Assessment of the Sector

The availability of critical raw materials and goods plays a vital role in U.S. defense supply chains, especially in the production of hypersonic systems. Current hypersonics supply

[1] This is an excerpt from a larger study. The full study (including the full list of contributors) is available here: https://www.emergingtechnologiesinstitute.org/publications/research-papers/hypersonics

chains face a plethora of vulnerabilities, including foreign dependency for sourcing. Although additional vulnerabilities may exist, this section will highlight those most pressing as well as provide recommended solutions to establish healthy and resilient hypersonics supply chains for the future.

High Temperature Materials

High temperature materials have numerous applications in hypersonic systems including heat shields, thermal protection systems, rocket engine components, scramjet engine components, nozzles, and especially leading edges. The materials used for various high-temperature components include:

Carbon Fiber

Carbon fiber's physical and mechanical properties make it a preferred choice in the aerospace and defense industry. It is lightweight, durable, corrosion-resistant, chemical-resistant, and temperature-resistant. Carbon fiber is a key component of high temperature materials including carbon-carbon composites, silicon carbide, silicon carbon fiber, phenolic-impregnated carbon ablator (PICA), and ceramic matrix composites. Approximately 90% of all carbon fibers are manufactured using a policyacrylonitrile (PAN) process while the remaining 10% use a rayon or petroleum pitch process (*How is Carbon Fiber Made?,* 2022). The United States and Japan are the top two carbon fiber producers (Sloan, 2020). With significant production occurring domestically and in an allied country, the carbon fiber supply chain is relatively healthy and secure. However, potential market shifts may introduce risk in the future (Sloan, 2020). According to a recent Market Research report, "The global carbon fiber market was valued at USD $6.5 billion in 2022 and is projected to reach $21.7 billion by 2032" (*Carbon Fiber Market*, 2023). While there are numerous industries that rely on carbon fiber, "aerospace and defense accounted for 44.2% in terms of value in the carbon fiber market in 2022" (*Carbon Fiber Market*, 2023). The wind energy industry accounts for the second largest share at 14.7% of share in terms of value (*Carbon Fiber Market*, 2023). As countries impose strict environmental policies, the demand for carbon fiber (especially in the wind energy industry) will likely increase. According to recent estimates, with rapidly increasing demand, the carbon fiber market could see a potential shortfall of 55,250 metric tons by 2026 (Sloan, 2021). Shortages in carbon fiber have existed in the past and suppliers have added additional capacity (*Carbon Fiber Market*, 2023). However, it can take a minimum of two years to construct and commission a new carbon fiber line (Sloan, 2021). With an increased emphasis by the government world-wide on alternative sources of energy, including wind, this could negatively impact the availability of carbon fiber, in the short-term, for aerospace and defense uses, including hypersonics (Sloan, 2021). At the same time though, in the long-term, growth of carbon fiber supply could benefit hypersonics supply chains. However, only time will tell if the carbon fiber industry can grow quickly and sufficiently to support all end uses including hypersonics.

Carbon-Carbon and Ceramic Matrix Composites

Carbon-carbon and ceramic matrix composites are lightweight, strong, and stiff materials that remain durable even at very high temperatures (*Hypersonic Composites Resist Extreme Heat and Stress*, 2007). Carbon-carbon is the only option for coatings for the higher speed hypersonic systems. Because these composites have only niche applications and DoD demand is low, the supply base is relatively small, and most coatings are made by hand. According to industry participants in the working groups, there are only three suppliers for the carbon-carbon composites used in hypersonic vehicle coatings. The lack of a consistent market has led to a very fragile supply chain. Given these risks, some defense prime contractors are acquiring high temperature material manufacturers in order to guarantee availability (Mason, 2022). The DoD has taken notice of the fragile supply chain and is funding the University of Buffalo through LIFT, a DoD Manufacturing Institute to research alternate materials (Brothers, 2022). In December

2022, the DoD also awarded $22.9 million for expanded domestic production of high- and ultra-high temperature composites (Martinez & Bistarkey, 2022). These are both steps in the right direction but will likely take a significant amount of time to yield results. In the near-term, the current size of the supply base is a significant barrier to scaling hypersonic systems.

Tantalum

While tantalum has many other applications, it is an important component in tantalum carbide, an ultra-high temperature ceramic, with significant applications in hypersonic systems, given its high melting point (3880 degrees C; Canan, 2007). Tantalum powder also offers a highly corrosion-resistant, strong, and pure material. Its unique properties enable industry to 3D print components for aerospace and defense applications. Finally, tantalum is also used in manufacturing micro- electronics which are found in hypersonic systems. There are three import streams of tantalum to the United States: 1) ores and concentrates, 2) metal and powder, 3) waste and scrap (Friedline, 2023). From 2018-2021, the U.S. imported most of its tantalum ores and concentrates from Australia (43%) and Rwanda (21%), (Friedline, 2023) metal and powder from China (42%) and Germany (23%), and waste and scrap from Indonesia (23%) and China (17%; Friedline, 2023). Tantalum metal and powder are the product of processing ores and concentrates, which are then used to make alloys designed for different purposes. While tantalum is included in the National Defense Stockpile, thus providing limited insurance against supply issues in case of unexpected, increased demand, there is significant concern surrounding the percentage of U.S. tantalum metal and powder, and waste and scrap that originate from China. It is not clear from open-source information if tantalum for hypersonic uses is imported as ores and concentrates, metal and powder, or waste and scrap. Therefore, it is unclear how much risk is introduced into the supply chain due to reliance on China. If the majority of tantalum for hypersonic systems is imported as ores and concentrates, this supply chain is relatively secure and stable with reliance on a close U.S. ally. However, if the necessary tantalum quantities are imported as metal and powder or waste and scrap, Chinese production introduces significant risk into this aspect of the supply chain.

Rare Earth Elements

The supply of rare earth elements (REE), consisting of the 15 lanthanides on the periodic table plus scandium and yttrium, has been the subject of much discussion in the public forum over the past decade for applications that go far beyond hypersonics (*What are rare earth elements, and why are they important?,* 2023). Although several rare earth elements have hypersonic applications, one of the most important is yttrium, a key component of ceramic applications including high temperature refractories for continuous-casting nozzles (Gambogi, 2020). According to U.S. Geological Survey data, Chinese exports of refined rare-earth metals account for 74% of U.S. rare-earth imports from 2018–2021 (U.S. Geological Survey, 2023). China not only mines the rare earth elements, but also controls more than 85% the world's processing capacity (International Energy Agency, 2021a). The only current domestic rare earths mining alternative to China is California's Mountain Pass mine, operated by MP Materials. In 2020, MP Materials extracted 38,503 tons of material, (MP Materials, 2021) compared to Chinese extraction reported at 140,000 tons in 2020 (Daly, 2021). However, MP Materials' raw material is sent to a subsidiary of the China-based firm, Shenghe Resources Holding Co. Ltd., for processing (United States Securities and Exchange Commission, 2022; Easley, 2023) In 2021, Mountain Pass Mine in California received $10 million in funding from the Department of Defense to "help it build a $200 million refinement facility for light rare earths" (Magnuson, 2021). With help from the DoD funding, processing for some light rare earths will be onshored, thus eliminating some reliance on China. At the same time, Round Top Mine in Texas, operated by USA Rare Earth, has similar goals to mine and process rare earths domestically. In 2020, USA Rare Earth opened a pilot processing facility in Wheat Ridge, CO with the goal of being “the first processing facility outside of China with the ability to separate the full range of rare earths” (Svaldi, 2020). While these recent developments are encouraging, mining and processing take time to reach full capacity. As such, the United States will continue to be reliant on China for REE mining and processing, thus posing a direct vulnerability to numerous defense and non-defense applications, including hypersonics.

Other Raw Materials and Goods

Ammonium Perchlorate

Until recently, the DoD relied on a single source for ammonium perchlorate (AP), a key component of hypersonic systems. AP is a principal raw material used in solid rocket propellants, and until recently, was sourced only from American Pacific (AMPAC). AMPAC was the only DoD-approved, North American supplier of the material since the company merged with Pacific Engineering and Production Company of Nevada in the 1980s (Judson, 2017). The U.S. government actually assisted in consolidating the businesses following an industrial accident, the largest non-nuclear explosion in U.S. history at an AMPAC facility in 1988 (Judson, 2017). Advocates for the merger claimed it would drive down the cost of ammonium perchlorate due to economies of scale (Judson, 2017). However, the second-order effects were significant vulnerabilities in the supply chain for solid rocket propellants with a single point of failure, higher prices due to lack of competition, and therefore a vulnerability for hypersonic systems. However, starting in 2016, Northrop Grumman (NG) stood up AP production for internal evaluation, increasing to full design production by 2019/2020.[2] NG’s decision to begin producing AP at its location in Promontory, UT, was based on a desire to create competition in response to rising prices. NG is now a qualified supplier of AP to the U.S. government for multiple programs including hypersonic-related programs. Only time will tell if two AP suppliers for hypersonic purposes is sufficient. However, a second entrant into the market reduces the risks associated with a single supplier and will likely reduce costs, due to competition.

Summary

Critical raw materials and goods in hypersonics supply chains face several challenges, including foreign source reliance and shortages due to the pandemic and other factors. While some pose significant vulnerabilities in the hypersonics supply chains, like rare earth elements, others, like plastics, face short-term challenges that may be righted by economic forces over time. In some cases where there is a challenge for future supply, industry and the DoD have begun to look for alternatives but these efforts needs to be expanded and fully resourced. Of the materials discussed in this chapter, high-temperature materials and the raw materials necessary for them are the most critical. The following recommendations should be implemented to ensure secure hypersonics supply chains in the future.

Recommendations

- Working together, Congress and the Department of Defense should reinforce the National Defense Stockpile of strategic minerals.
- The DoD should provide a clear demand signal to private industry to increase investment in additional carbon fiber suppliers.

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[2] All Northrop Grumman information was gathered via e-mails with the company.

Manufacturing Base and Workforce

Assessment of the Sector

The U.S. manufacturing base and workforce is essential to the defense industrial base's ability to develop and deliver hypersonic capabilities at scale. While not traditionally considered part of a supply chain, testing infrastructure is a key component of delivering hypersonic systems and therefore was also considered by the working groups. During the ETI-led working groups, participants assessed the health of the current manufacturing base and workforce by addressing key issues, areas of success, and opportunities for improvement through policy changes. Overall, the existing hypersonic manufacturing base and testing infrastructure is insufficient to meet the needs of the future. At the same time, the accompanying hypersonic workforce has waned over the years and cannot meet the current, much less, future demands. Over the past few years, some positive steps have been taken, however, it is not enough.

Manufacturing Base

Insufficient Manufacturing Base Due To Inconsistent Demand Signal

Throughout the hypersonic working group discussions, a common theme from industry and academia was a lack of consistent government demand signal when it comes to hypersonics. As such, the existing manufacturing base is small and suited only to manufacturing small numbers of hypersonic systems with long lead times. In recent years, DoD leadership has attempted to send a clearer demand signal for hypersonic systems by stating the need for "hundreds in a short period of time" and according to one official, potentially even thousands or tens of thousands (Freedberg, 2020). This, in theory, would be a tremendous leap from the current demand for a handful of prototypes, if supported by budget requests and appropriations. The current manufacturing base cannot produce hypersonic systems at that scale due to several issues that will be addressed in this section. Solutions are also presented but must be implemented quickly to create secure, resilient supply chains to supply hypersonic systems at scale.

Limited Suppliers

According to several working group participants, the hypersonic manufacturing base relies on a relatively limited supply base. As noted in the Critical Raw Materials and Goods section, many materials used in hypersonic systems are highly specialized and do not have extensive commercial applications, which limits the number of companies participating in the market. For example, there are only two U.S. suppliers of rocket motors used in missile propulsion systems: Aerojet Rocketdyne and Orbital ATK. Orbital ATK was acquired by Northrop Grumman in 2018, while Aerojet Rocketdyne is set to be acquired by L3 Harris Technologies in 2023, pending government approval (L3Harris Technologies, 2022). As prime defense contractors depend on propulsion system components for hypersonic vehicles, reliance on only two entities may be driving costs up (due to a lack of competition) and creating a potential point of failure in the supply chain. Hypersonic systems are only a small percentage of the rocket motor market, with the space industry making up the majority. As the proliferation of space continues to take off, this will put increased demand on an already limited supply, potentially channeling finite resources away from hyper-sonics development. According to one industry participant, limited supplier issues also exist with hypersonic structural components like Titanium-Zirconium-Molybdenum (TZM) bolts that are used to provide strength at elevated temperatures, as well as protective items such as thermal blankets that shield the vehicle from excessive heat. Because the commercial market is almost nonexistent for these materials, the industrial base remains small, and the market remains fragile due to inconsistent demand. Finally, due to the limited number of second- and third-tier suppliers for critical hypersonics components, prime defense contractors often share vendors. For example, Lockheed Martin and Raytheon are both reliant on the same suppliers for radar equipment, propulsion systems, satellite electronics, and semiconductor chips. This creates a potential vulnerability in supplier overlap and limited suppliers. As discussed in the Critical Raw Materials and Goods section, there is a limited supply base for high temperature materials. This need, in particular, has been recognized and Purdue University's Hypersonics Advanced Manufacturing Technology Center (HAMTC) is currently heading an effort with several leading defense contractors to produce high-temperature materials necessary for hypersonic flight. Research in advanced manufacturing capabilities will play a vital role in the study of these materials, but the effort cannot stop there. Both industry and government need to consider more investment in these alternative production techniques for improving the technological capability needed for tomorrow's hypersonic systems.

Advanced Manufacturing

Advanced manufacturing, and in particular additive manufacturing (AM), has the potential to enable industry to cost-effectively increase production. According to the Deputy Director of the Office of the Secretary of Defense's Manufacturing Technology Program, "The science has proven it's possible, but the practice is not widespread enough" (Albon, 2022). The hypersonic industry has already seen significant improvements in weapon design and cost reduction, through AM. According to two industry participants, AM has resulted in 20 times the reduction in the number of components required when compared to the X-51. This progress is paramount to the scaling of hypersonic weapons, as decreasing the number of parts also reduces the number of potential failure points. According to the same industry participants, the subsequent effect is an 8-fold decrease in cost accompanied by the part reduction and a 4.5-fold reduction in lead time for components.

As a general practice, AM is not a blanket application. However, some hypersonic systems require intricate geometric specifications that traditional manufacturing processes are unable to meet or are too expensive to produce at scale. This has led the DoD to request prototype solutions for its Growing Additive Manufacturing Maturity for Airbreathing Hypersonics (GAMMA-H) challenge (OSD Manufacturing Technology Program, 2022). The objective is for AM companies to address propulsion and high temperature requirements for systems traveling at Mach 5 or higher.

These benefits not only improve the performance of the weapon, but also drive the justification for companies to invest in AM. While AM will disproportionately affect air-breathing systems, there are multiple areas of hypersonic weapon design that lend themselves best to new manufacturing techniques. These include liquid rocket motors that use a fuel-cooled design. AM can improve both the thermal performance of the engine as well as the overall performance. Ultimately, reducing the cost of the engine and advancing its performance is critical for scaling up production. Design flexibility is also suitable for highly complex components, such as heat exchangers, optimized topologies, or complex cooling channels. Finally, AM could be used for wiring, antennae, and circuit boards to reduce weight, according to an industry participant.

Overall, AM reduces the number of components and people involved in the manufacturing process and eliminates tooling. For design complexity, AM achieves a performance that cannot be accomplished with conventional techniques. Advanced manufacturing also includes new technologies, such as big data collection, simulation software, and machine learning, which monitor AM processes by predicting stress and part distortion. The convergence of modern technologies advances hypersonic technology by removing welding, unnecessary machine operations, and joints. However, when considering where AM techniques can be applied, it should be noted that the materials needed ought to exist in sufficient quantities either through domestic or allied sources. Nevertheless, this improvement in manufacturing methods can substantially improve lead time and cost overall for hypersonic systems.

Unit Cost

Because hypersonics supply chains are still fairly nascent, the cost per unit—particularly for early prototypes and low-rate production systems—has been relatively high, though estimates are all preliminary and include different assumptions. Since specialty materials are not widely available, nor produced at scale, this drives the cost up overall. A constant message heard from senior DoD and Congressional leadership is the need to reduce the cost per unit for hypersonic systems. As Under Secretary of Defense for Research and Engineering Heidi Shyu explained, "We need to figure out how to drive towards more affordable hypersonics. And that's a piece I would like to help industry focus on: how can we develop affordable hypersonics materials and manufacturing processes to drive the cost down?" (Harper, 2021).

It is important to note that system affordability is not quantifiable per se, since it depends on a complex set of prioritization decisions within the Pentagon, White House, Congress, and industry. However, there are several different factors, regarding the capability of hypersonic systems, that can and should be taken into consideration. First, for hypersonic cruise missiles, a comparison could be made to the cost of conventional cruise missiles which typically cost approximately $1 million per unit (Cohn et al., 2019). However, a hypersonic cruise missile brings far more capability than a conventional cruise missile, namely, speed and maneuverability, which makes defending against the missiles far more challenging. This increased capability will likely increase development, production, and sustainment costs. It is estimated that air-breathing systems—based on DARPA's HAWC program—will cost approximately $2 million per missile. This is a significant drop from the current cost of "tens of millions per unit" currently associated with hypersonic cruise missiles (Stone, 2021). On the other hand, the Navy's CPS program and the Army's LHRW provide a very different capability and thus are estimated to cost $50 million (*The U.S. Army's Long-Range Hypersonic Weapon [LRHW]*, 2023). These estimates are all very preliminary, include different assumptions, are based on limited data and analysis, and are sometimes biased by industry and service parochialism. It is important to note that some reduction in cost will occur through economies of scale as the Department purchases a larger number of hypersonic systems. However, in order to bring the cost in line with the above estimates in the future, significant changes will have to occur in the hypersonics manufacturing base overall.

Long Lead Times

Due to the lack of demand for large quantities of hypersonic weapons and a low supply of components, lead times have grown exponentially. This issue was raised by multiple working group participants regarding several different components. The current long lead times, in turn, prevent the hypersonic industry from moving quickly. Because the United States is still in the prototype phase of fielding hypersonic systems, there is little economic incentive for multiple hypersonic component suppliers to enter the market and, therefore, reduce lead time. Overall, the longer lead time does not only apply only to hypersonics, but across the defense manufacturing ecosystem. Competition for components goes beyond military applications, as the defense industry must compete for resources with non-defense commercial companies, creating strains on the supply chains of products and components even where the DoD is the sole customer. As discussed elsewhere in the report, this is especially true for components that overlap with commercial aerospace and space applications. Given the tremendous recent growth in the space industry, this competition for components and resources will likely continue. However, in the long-term, this overlap could benefit hypersonics by growing the supply base to meet increasing demand.

Testing Infrastructure

Testing infrastructure, while not traditionally considered as a component of supply chains, plays a crucial role in moving hypersonic systems from the early developmental phase to a fully fielded system. Therefore, it was deemed within the purview of this study. A constant theme throughout the working groups was the insufficiency of current national hypersonics testing infrastructure. While a full, detailed analysis of testing infrastructure could be the subject of an entire study, and has been on several occasions, this report will only touch on a few key issues.[3]

There are two broad categories of test facilities needed for the maturation of hypersonic technologies—ground and flight. The first category includes hypersonic wind tunnels (HWTs), that are generally less expensive to operate and allow for easier collection of data compared to actual flight. HWTs simulate air flow and ultra-high temperatures that hypersonic vehicles need to withstand in-flight. The second category is an open-air range, which enables actual flight of a hypersonic prototype or testbed. Open-air ranges provide the space for putting a hypersonic missile on the vehicle's surface itself, enabling testers to better mimic the conditions of the atmosphere. Both facilities simulate the unique conditions experienced in hypersonic flight (e.g., speed, pressure, and heating) and are instrumental for hypersonic development.

Among the biggest constraints to the development of hypersonic technology is the inadequate testing infrastructure in the United States. According to a study conducted by the Institute for Defense Analyses (IDA), the United States had only 48 specialized hypersonic test facilities and mobile assets in 2014 (*The U.S. Army's Long-Range Hypersonic Weapon [LRHW]*, 2023). The facilities are a mix of government, academic, and business entities, including: 10 DoD hypersonic ground test facilities, 11 DoD open-air ranges, 11 DoD mobile assets, 9 NASA facilities, 2 Department of Energy (DoE) facilities, and 5 industry or academic facilities" (*Hypersonic Weapons: Background and Issues for Congress*, 2023). While this study was completed almost 10 years ago, only a few minor changes have occurred since. Two encouraging developments (that will be discussed in more detail below) are that a few universities have begun building additional testing facilities and the DoD has very slowly begun to explore limited changes to increase testing infrastructure. It is challenging to quantify exactly how many more facilities are needed. However, additional capacity is required for several different reasons raised by working group participants.

First, hypersonic systems must compete for test time slots with current high-priority programs, such as missile defense and nuclear deterrence. While DoD leadership has emphasized the importance of hypersonic systems, these other programs have been prioritized in scheduling tests. This is partly due to a lack of a hypersonics program of record and due to the other programs being prioritized by the DoD. The ensuing limited range access for hypersonic flight testing creates inefficiencies. As hypersonic tests are pushed from the schedule to make room for established programs of record, this causes cascading delays to technological development as programs wait months to reschedule (Albon & Gould, 2022). Consistent access to these facilities for ground testing is particularly vital to determine which materials are needed for hypersonic development. One workshop participant noted that optical window materials, for example, have been an ongoing concern for industry, in part because of limited testing capacity. Experiments testing optical window materials in hypersonic flow are necessary to address challenges related to efficient cooling at high speeds and the ensuing high temperatures (Mi et al., 2023). Studies dating back to the 1980s and current SBIR/STTR

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3 For examples, see "Advanced Hypersonics Test Facilities" edited by Frank Lu and Dan Marren or "Study on the Ability of the U.S. Test and Evaluation Infrastructure to Effectively and Efficiently Mature Hypersonic Technologies for Defense Systems Development: Summary Analysis and Assessment, Institute for Defense Analyses, September 2014."

contracts attempt to provide solutions to address this challenge (Tropf et al., 2023). However, the longevity of the issue reflects the poor quality of testing, which hinders industry's ability to collect the appropriate amount of data to adequately pull meaningful results.

A second issue is the age of existing testing infrastructure. Most testing facilities were built decades ago and personnel at the facilities are not accustomed to working at the tempo that is now necessary to keep up with all programs. With this high operational tempo, fatigue sets in and machines break. When one machine goes offline, there is not enough redundancy built in and testing is temporarily halted. Older testing infrastructure also lacks efficient data acquisition. If data acquisition was modernized at testing facilities, this could reduce the number of tests necessary since each test could yield significantly more data.

Current modes of testing also tend to be extremely expensive and difficult to coordinate. For example, the Navy's CPS system has required a "string of pearls" of ship-borne assets across the ocean in order to collect data (U.S. Department of Defense, Office of Operational Test & Evaluation, 2023). However, the Test Resource Management Center (TRMC) is attempting to address this through the SkyRange program, which uses twenty RQ-4B Global Hawks as hypersonic test support (Hoeven, 2022). The goal of the SkyRange program is to increase hypersonic testing, meeting the Department's test cadence of "50 plus tests a year" (Albon, 2022). TRMC and the Office of the Principal Director for Hypersonics are also working with the Space Development Agency, Space Force, and Army to study how satellites could be used to support hypersonic testing (Albon, 2022). TRMC is also leading the development of the Multi-Service Advanced Capability Hypersonics Test Bed (MACH-TB) program, which aims to validate and field hypersonic systems at a higher frequency through a new testing facility (DoD, 2022). Each of these programs are a step in the right direction but only time will tell if they are successful.

Finally, even once the current first-generation hypersonic systems have reached sustainment, modernized, expanded testing facilities will still be needed for the future. A higher tempo of regular S&T flight testing will be necessary to solve key S&T or physics questions for future generation hypersonic systems. Furthermore, as systems are continuously updated with more modern software, materials, and microelectronics, significant continuous testing of the system and subsystems will be required.

Overall, the current U.S. testing infrastructure is insufficient to meet the demands laid out by the Defense Department itself for hypersonic development over the coming years. Even if the rest of the hypersonics manufacturing base were scaled up, aging testing infrastructure would significantly hinder production. Therefore, modernizing and expanding testing infrastructure to support hypersonic programs is a necessary link of a secure, resilient supply chain.

Workforce

Lack of Hypersonic Talent

The hypersonics industry—defined by a workforce lacking substantial experience working on large-scale hypersonic projects—faces an uphill battle in developing a stable supply of hypersonic professionals due to the volatile history of the technology's development. Unfortunately, it is difficult to estimate exactly how large the existing hypersonics workforce is in order to then determine what type of growth is necessary over the coming years. However, a few conclusions can be drawn from the insights of the working groups, subsequent interviews with experts in the field, and internal research. At the same time, trends from the larger aerospace industry workforce likely impact the hypersonics workforce as well and should be considered. As such, this section will summarize the key insights and concerns from the working groups, inter- views with experts, and internal research in the larger context of the aerospace industry workforce, and attempt to provide actionable recommendations to address them.

Overall, the aerospace industry faces many of the same issues facing other sectors in the post-Covid era (Aerospace Industries Association, 2022). The industry has seen rising employee turnover with 69% of respondents to a 2022 Aerospace Industries Association survey stating that turnover increased in the last 12 months (Aerospace Industries Association, 2022). At the same time, there are reports of an industry-wide shortage of talent, especially for workers with engineering skills and strong digital capabilities, despite increasing demand due to the rebound of air travel from the pandemic, the need for advanced defense capabilities due to rising geopolitical tensions, and a renewed vision and prioritization of space travel and deep space exploration (Aerospace Industries Association, 2022). The hypersonics workforce, as a subset of the larger aerospace industry workforce, likely faces similar challenges that are compounded by additional concerns raised by the working groups. According to one working group participant, the current hypersonic-specific expertise is unbalanced and misaligned to current needs. There is a plethora of early and mid-career aerothermal expertise, but a dearth of expertise in other needed areas such as hypersonic controls, system design, and high temperature materials. At the same time, the current hypersonics workforce lacks experience working on large-scale prototypes and system integration challenges as systems scale up from R&D to production.

The hypersonic workforce can be divided into five general groups, along the lines of five different aspects of the technology (United States Air Force Scientific Advisory Board, 2000):

1. Hypersonic-specific technology experts. Certain requisite expertise is applicable only to hypersonic vehicles and their flight regime. Development of the necessary knowledge and expertise in these technology areas requires specific study and experience accrued over a period of years.
2. Workforce that can adapt existing technologies to the specific applications of hypersonics. Other technologies used in vehicle design must be adapted to the severe hypersonic environment. It is likely that technologies from other flight regimes can be adapted to the hypersonic environment. Under some circumstances this can be better and more cost-effective than creating new and unique disciplines.
3. Workforce that combines structures, aerodynamics, engines, communications, sensors, controls, etc., into an integrated operational system. The lack of personnel experienced in vehicle integration and overall hypersonics systems engineering is perhaps the most important issue facing the hypersonic workforce today.
4. Project management for hypersonic vehicle development. The integrated design, building, and testing of a hypersonic vehicle requires project managers with unique expertise. This expertise is largely due to special aspects of components used in the hypersonic environment and the blending and integration of those components into a vehicle.
5. Craftsmen and supporting staff, including machinists, technicians, and other skilled experts. The craftsmen include individuals responsible for activities like installing wind tunnel models, installing instrumentation, precision machining, and systems and infrastructure maintenance and repair. On the supporting side are those who are not subject matter experts, but instead can support engineering activities and rationalize the overarching policy, management, market dynamics, and other business factors that will shape and control program activities.

According to the working groups and interviews with experts, each of these hypersonics workforce sectors faces its own challenges and issues. First, the workforce overall is dominated by late-career professionals and thus a portion is close to retirement. Among the aerospace and defense talent, 28% of the workforce is aged 55 and older, and 42% of the overall workforce has less than five years of tenure at their current company (Aerospace Industries Association, 2022). The working group participants described a similar hypersonics workforce. This is likely due to a heavy emphasis by the U.S. government on hypersonic systems several decades ago. This emphasis led to an increased number of professionals entering the hypersonics workforce. However, that emphasis has ebbed and flowed over the years, and with the uncertainty, fewer professionals have entered the workforce. Another important insight from the working groups pertained to the level of education necessary to work in hypersonics. While certain jobs may require a doctoral level of education, for much of the hypersonic workforce a bachelor's, master's, or even a high school diploma is sufficient. In addition to an aging hypersonics workforce and the necessity for professionals with varying levels of education, several other factors were highlighted by the working groups and experts as impacting the workforce.

Clearance Process Stymies Development of Needed Workforce

Though not specific to hypersonics, the clearance process keeps the industry from moving quickly. Participants in the working groups highlighted that this issue affects nearly all sectors of the workforce and at all levels. One particular issue raised in the working groups is the challenge of clearing students so they can work on relevant research while still in school and be ready to join the workforce immediately upon graduation. Similar issues plague mid-and-senior level talent as well. With clearance processing timelines of 12–18 months, valuable time is wasted. This is an issue that goes far beyond hypersonics, but if hypersonic systems are truly a priority for the DoD and there is a need to move quickly, this talent supply chain issue must be addressed.

Summary

Both the current hypersonics manufacturing base and the hypersonics workforce are insufficient to support hypersonics production in the future. While multiple issues plague both sectors, a lack of consistent demand signal from the Department of Defense has exacerbated the problem. Without a guaranteed return on investment, companies will not invest time, money, and resources into scaling up production. At the same time, individuals may not enter the hypersonics workforce if the viability of programs, and therefore positions, is in question. The first step in scaling up the hypersonics industrial base must be a consistent demand signal from the government. Several other steps must also be taken in order to secure hypersonics supply chains for the future.

Recommendations

- The Department of Defense should provide a consistent and clear demand signal to industry by treating certain hypersonic programs as traditional Programs of Record and utilizing multi-year contracts to send an extended demand signal.
- Additional testing infrastructure should be funded jointly by the DoD and industry at appropriate academic institutions to help replace aging testing infrastructure.
- The DoD should increase the hypersonics flight test schedule.
- The DoD should encourage venture capital to invest in areas where the hypersonics supply chains and growth of the space industry overlap.
- Academia should be leveraged, via the University Consortium for Applied Hypersonics (UCAH), to educate mid-level hypersonic talent.

Supply Chain Security and Vulnerabilities

Assessment of the Sector

Hypersonics supply chains, like other emerging technology supply chains, face a range of threats related to cybersecurity, counterintelligence, and intellectual property theft. While hypersonic-specific examples can be challenging to find in open-source information, some significant conclusions can be drawn from an analysis of recent and historical examples from related industries, in addition to issues raised by the working group participants.

Cybersecurity Risks

Cybersecurity threats to hypersonics supply chains begin at the very lowest tier: mining and production of critical raw materials. As mining operations become more automated, the attack surface area increases (Huq, 2016). Over the years, mining operations have been subject to attacks from numerous fronts, including nation-state actors, with the same techniques used in other sectors such as phishing, vulnerability exploitation, watering hole attacks, and infected equipment (Huq, 2016). The goals of such attacks can range widely from commercial espionage to information operations. For example, from 2006 to 2014, aluminum maker Alcoa Inc. and metal supplier Allegheny Technologies Inc. (ATI) were subject to attacks allegedly originating from the Chinese People's Liberation Army (PLA; Huq, 2016; Mufson, 2014). While exact details are unclear, the hack seemed focused on gaining internal messages related to a February 2008 partnership with a Chinese state-owned company to acquire a substantial stake in a foreign mining company (Huq, 2016; Mufson, 2014). ATI also entered a joint venture with a Chinese state-owned company in 2012 (Strohm et al., 2014). During the attack, the hackers allegedly gained access to network credentials for virtually every employee at a company with approximately 9,500 full-time employees in the aerospace, defense and "specialty materials solutions" sectors (Kravets, 2014).

More recently, an American cybersecurity firm reported on efforts by the People's Republic of China (PRC) related to a "subset of information operations activity . . . across social media that targeted the Australian rare earths mining company, Lynas Rare Earths Ltd." (Mandiant Threat Intelligence, 2022). The activity was one small part of a larger influence campaign, called DRAGONBRIDGE, intended to promote "various narratives in support of the political interests of the PRC" (Mandiant Threat Intelligence, 2022). Not long after, additional attacks took place against the Canadian rare earths miner, Appia, and the American rare earths supplier, USA Rare Earths, in response to reports that Appia had discovered "a new rare earths bearing zone in Northern Saskatchewan" and USA Rare Earths announcing "plans for a rare earths processing facility" (Mandiant Threat Intelligence, 2022). It is likely that the Chinese Communist Party (CCP) saw these commercial entities challenging their dominance in rare earth mining and processing as a threat and thus attempted to undermine the credibility of those commercial entities (Mandiant Threat Intelligence, 2022).

Moving up through the supply chain, hypersonic system manufacturers may face similar cyber threats. According to reporting by the Cybersecurity and Infrastructure Security Agency (CISA), Russian state-sponsored cyber actors have targeted small and large U.S. cleared defense contractors (CDCs) and subcontractors "with varying levels of cybersecurity protocols and resources" (Cybersecurity & Infrastructure Security Agency, 2022). While the exact companies are not named, CISA reports that the CDCs are supporting contracts for the DoD on "command, control, communications, and combat systems . . . weapons and missile development; vehicle aircraft design; and software development, data analytics, computers, and logistics" (Cybersecurity & Infrastructure Security Agency, 2022). Given the breadth of systems targeted, and the fact that Russia has had a robust hypersonics program over the years, it is possible that CDCs working on hypersonics systems are among those targeted.

During the working groups, industry members raised several similar cybersecurity concerns that they, or their suppliers, face on a regular basis. First, the smaller, low-tier suppliers lack the necessary resources for robust cybersecurity measures. The business case is almost non-existent for these small companies to invest in the necessary infrastructure for cybersecurity measures unless they can make a profit in five years—a challenge when the customer is the DoD. Another cyber vulnerability raised by working group participants was the issue of software supply chain attacks. A few suppliers use foreign-made software, which may leave them vulnerable to attacks. According to the CSIS Significant Incident Reports, numerous Chinese hackers have also engaged in cyberattacks against U.S. aerospace companies over the years, including using a malware known as "Sykipot" to target U.S. defense aerospace companies (*Survey of Chinese Espionage in the United States Since 2000*, 2023).

Universities and National Labs conducting hypersonics research and testing have also faced cyberattacks over the years. In 2018, the Australian National University (ANU), which conducts hypersonics research, was allegedly breached by Chinese hackers (Borys, 2018). Exact details are unclear, but according to Australian Strategic Policy Institute's executive director Peter Jennings, the goal of the attack was to access and extract intellectual property from the institution (Borys, 2018). Oak Ridge National Lab, which has conducted significant research pertaining to modeling the flow of objects in hypersonic flights as well as research aimed at understanding combustion at hypersonic speeds, was subject to a sophisticated cyberattack in 2011 (Liebowitz, 2011). Although full details on the attack are unclear, the lab was forced to shut down its e-mail systems and internet access for all employees when they discovered they were a victim of an advanced persistent threat to steal technical data (*Survey of Chinese Espionage in the United States Since 2000*, 2023). Again, it is unclear if these attacks directly targeted hypersonics research and data, but these examples still show significant cyber vulnerabilities within organizations at various levels of hypersonics supply chains.

Counterintelligence and Economic Espionage Risks

While many current counterintelligence threats to hypersonics supply chains may be classified or not available in the public domain, it is possible to evaluate potential threats based on the reported actions of adversaries and similar historical examples.

China's technology transfer efforts have become well-known over the past several years. President Xi Jinping has emphasized that in order for China to "grow strong, prosperous and rejuvenated," (Murphy et al., 2021) it must "become the world's main center of science and the high ground of innovation" (Murphy et al., 2021) Hypersonics is just one example where China has used both legal and illegal means to field a technology before the United States (Cadell & Nakashima, 2022). Research and development of hypersonic systems in the United States began as early as the 1960s, while Chinese work did not begin in earnest until the mid-2000s (Wood & Cliff, 2020). Given a nearly 40-year difference, how is it that the United States has yet to field a single hypersonic weapon, while China has fielded several and conducted multiple tests on others? While the answer is long and complicated, one factor that potentially accelerated the Chinese programs was the legal, or illegal, acquisition of U.S. research and technology. To be sure, the United States failed to maintain the momentum of its hypersonic programs over the years. If the momentum had been maintained and a clear, consistent focus on fielding hypersonic systems had continued, the United States not only would have outpaced China but many of the existing hypersonics supply chains issues would perhaps not exist. Unfortunately, the reality is that early on, China took note of U.S. hypersonic work, including several open policy documents that explained the value of hypersonic weapons (*America's Air Force: A Call to the Future*, 2014; Wood & Cliff, 2020) As the United States wavered in its commitment to fielding these weapons, China took advantage of the previous work conducted by the United States and others to expedite their hypersonic programs.

According to a recent report on the issue, China also recruited several former scientists from Los Alamos National Lab to work on their hypersonics programs (Strider, 2022). One example is Chen Shiyi, an expert in fluid dynamics and turbulence, “who has made major contributions to China’s hypersonic missile and aerodynamics programs” (Strider, 2022). After working at Los Alamos National Lab from 1990–2000 and serving as the deputy director of the lab’s Center for Nonlinear Studies, Chen joined Johns Hopkins University in 2001 to serve as chair of the Department of Mechanical Engineering (Strider, 2022). In 2005, Chen returned to the PRC to help establish Peking University’s engineering college and eventually rose to the role of director of PKU’s State Key Laboratory of Turbulence and Complex Systems (LTCS) (Strider, 2022). Allegedly, research that used wind tunnels “built during Chen’s time as PKU engineering dean and LTCS director made ‘important contributions’ that allowed ‘the PRC to surpass the U.S. in airbreathing vehicle research and development” (Strider, 2022).

Chinese transfer of expertise for hypersonic programs reaches to the semiconductor level. In 2016, Qualcomm, an American semiconductor company, agreed to a joint venture with Huaxintong, a Chinese company, to develop server chips. While the joint venture was closed in 2019, after producing little of value, some expertise “appears to have transferred to other Chinese companies building . . . data center chips” (Miller, 2022). Allegedly, at least one chip design engineer left Huaxintong to work for Phytium, “which the U.S. later alleged had helped the Chinese military design advanced weapons systems like hypersonic missiles” (Miller, 2022). These are just a few examples of how China has legally, and illegally, built up its hypersonic programs with U.S. research and development (Strider, 2022).

Intellectual Property Theft

Another significant vulnerability in hypersonic system supply chains, and all defense supply chains, is intellectual property (IP) theft. Unfortunately, it is difficult to find hypersonic-specific examples of IP theft in open source. However, lessons can be learned by looking at IP theft across the DIB and other related industries. While IP theft can be committed by many different actors, the U.S. Department of Justice has increasingly publicized indictments of Chinese IP theft. In 2014, the FBI indicted five Chinese nationals for stealing trade secrets from American companies (*U.S. Charges Five Chinese Military Hackers for Cyber Espionage Against U.S. Corporations and a Labor Organization for Commercial Advantage*, 2014). While not a hypersonic-specific example, this was the first time the United States ever brought charges against a state actor for this type of hacking (*U.S. Charges Five Chinese Military Hackers for Cyber Espionage Against U.S. Corporations and a Labor Organization for Commercial Advantage*, 2014). Almost a decade later, it is challenging to accurately quantify the damage inflicted on U.S. companies through Chinese theft, however, a few examples can shed light on the issue. In September 2022, an engineer was sentenced to eight months in prison for theft of more than 500 files including trade secrets related to networking chips, that he took prior to resigning from his position at Broadcom (*Former Broadcom Engineer Sentenced to Eight Months in Prison for Theft of Trade Secrets*, 2022). Upon his resignation, he began working for a startup company in the PRC that was “seeking to become a leading chip designer focused on the PRC’s domestic market for networking chips at the time” (*Former Broadcom Engineer Sentenced to Eight Months in Prison for Theft of Trade Secrets*, 2022).

China has also initiated talent programs, including the “Thousand Talents Program” in order to “attract, recruit, and cultivate high-level scientific talent in furtherance of China’s scientific development, economic prosperity, and national security” (*Former West Virginia University Professor Pleads Guilty to Fraud That Enabled Him to Participate in the People’s Republic of China’s “Thousand Talents Plan”*, 2022). One such example was the case of Xioaqing Zheng. While Xiaoqing Zheng was an employee of General Electric, he stole valuable intellectual property on advances in gas turbine technologies (Burgess, 2021). Fortunately, GE stopped the flow of IP when their insider threat program monitoring received an anomaly alert (Burgess, 2021). However, until the alert, GE was ignorant of the fact that he was associated with the Chinese Thousand Talents Program for years (*Hospital Researcher Sentenced to Prison for Conspiring to Steal Trade Secrets, Sell Them in China*, 2021). In 2020, United Microelectronics Corporation (UMC), a Taiwanese semiconductor foundry pled guilty to criminal trade secret theft (U.S. Department of Justice, 2020a). According to the Justice Department, "UMC stole the trade secrets of an American leader in computer memory to enable China to achieve a strategic priority: self-sufficiency in computer memory production without spending its own time or money to earn it" (U.S. Department of Justice, 2020a).

Summary

While hypersonic-specific examples of IP theft, cyberattacks, and CI threats can be difficult to find in open source, several lessons can be learned from similar cases. First, cyberattacks can and do target all levels of the hypersonics supply chains including mining and processing of critical raw materials like REE and aluminum. Similarly, there have been clear examples of the PRC recruiting hypersonics talent from the United States to help build their programs. Finally, IP theft by the PRC has affected many companies and technologies that undergird hypersonics. Overall, there are a number of security vulnerabilities within the hypersonics supply chain that should be addressed by the government and industry.

Recommendations

- The DoD should address major cybersecurity risks at the low-to-mid-tier levels of the hypersonics supply chains by creating a "bug bounty" program for small government contractors working on hypersonics.
- The FBI should work with industry and academic leadership at all tiers of the hypersonics supply chain to increase awareness of counterintelligence threats.
- Industry leadership at all tiers of the hypersonics supply chain should increase awareness of intellectual property theft by foreign adversaries. In addition, industry leadership should take steps to identify and secure cyber vulnerabilities, and screen new and current employees.

International Partnerships and Allied Nearshoring

Assessment of the Sector

The United States places great value on maintaining alliances and partnerships with like-minded nations around the world to safeguard against growing threats. During the ETI-led working groups, participants assessed the challenges to international partnerships, identifying key issues, areas of success, and opportunities for improvements through policy changes. Overall, international partnerships in hypersonics are limited. Given the sensitive nature of hypersonics technology, this is understandable. However, some steps should be taken to strengthen and utilize existing partnerships to better secure hypersonics supply chains.

Current International Partnerships and Agreements on Hypersonics

Multilateral Partnerships

The United States currently has two multilateral partnerships in place on various aspects of hypersonics. First, through the AUKUS partnership, Australia, the United Kingdom, and the United States, agreed to increase trilateral collaboration on several defense capabilities and emerging technologies. Hypersonic and counter-hypersonic capabilities were explicitly named as areas where "AUKUS partners will work together to accelerate development" (The White House, 2022) Second, through the University Consortium for Applied Hypersonics (UCAH), the

United States is working with many international universities from the U.K. and Australia (University Consortium for Applied Hypersonics, 2022). While these partnerships are a good framework at the highest levels, there are significant opportunities that are not being used.

Bilateral Partnerships

The United States has bilateral partnerships with three countries related to hypersonic capabilities: Australia, Norway, and Japan. Beginning in 2007, the United States has collaborated with Australia first on the HIFiRE program and more recently on its successor program, SCIFiRE (*Hypersonic Weapons: Background and Issues for Congress*, 2023). The Hypersonic International Flight Research Experiment (HIFiRE) was a $54 million flight test program to develop hypersonic technologies, explore scramjet engine technologies, and, more recently, explore the flight dynamics of a Mach 8 hypersonic glide vehicle (*Hypersonic Weapons: Background and Issues for Congress*, 2023). The Southern Cross Integrated Flight Research Experiment (SCIFiRE) program is focused on further developing hypersonic air-breathing technologies with the goal of reaching a point where conducting demonstration tests in the mid-2020s would be possible (*Hypersonic Weapons: Background and Issues for Congress*, 2023). While these partnerships with Australia have been lauded as highly successful, they have faced some of the challenges that international partnerships often encounter. For example, in HIFiRE, some of the rockets needed for the flight tests contained asbestos, a material that could not be legally imported into Australia beyond a certain quantity. A military exemption was made to solve the issue, but that did not come without significant paperwork and associated delay—in this case, nearly two years. Unfortunately, collaboration with Australia has also faced challenges on the U.S. side. According to a working group participant, the program agreements (PAs) established by the U.S. DoD with Australia, were tied so tightly to a specific program, discipline, or application, that they impeded collaboration overall.

In early 2022, the United States announced that it would sign a new agreement with Japan to increase collaboration on the research and development of emerging technologies (Insinna, 2022). Among other technologies, the agreement focuses on advanced space systems and counter-hypersonic technologies (Insinna, 2022). In January 2023, the DoD announced the signing of a “bilateral Memorandum of Understanding for Research, Development, Test and Evaluation Projects” with the Japanese Ministry of Defense to improve defensive capabilities (DoD, 2023). Among other projects, counter-hypersonics was listed as an area for collaboration. While counter-hypersonics is not the focus of this report, this is still an important international partnership worth noting.

Finally, beginning in 2019, the U.S. Department of Defense and Norwegian Ministry of Defense announced a partnership on “the development of an advanced solid fuel ramjet that could find use in supersonic and hypersonic weaponry” (DoD, 2021a). The Tactical High-speed Offensive Ramjet for Extended Range, or THOR-ER, includes the U.S. Navy’s Naval Air Warfare Center Weapons Division, China Lake, and the Norwegian Defence Research Establishment and industry partner Nammo Group (DoD, 2021a). By 2024, the goal was to “not only have a flight demonstration but be able to transition the technology to the warfighter (DoD, 2021a). In 2022, the solid fuel ramjet missile was first flight tested, thus meeting the Phase 1 objective of demonstrating the capabilities of jointly developed propulsion technologies in flight (Saballa, 2022). While this partnership is viewed as valuable both technically and politically, and should therefore continue, the unsecure nature of the Andøya test facility, including its proximity to a peer competitor, poses challenges.

The existing bilateral and multilateral partnerships are a great step in the right direction. However, there are unused opportunities in these existing partnerships to help address current supply chain issues like lack of testing infrastructure, and resource dependency on adversaries.

Allied Nearshoring

As discussed in the Critical Raw Materials and Goods section, the United States is dangerously reliant on foreign adversaries for several critical raw materials relevant to hypersonic systems. While domestic onshoring might guarantee more secure sourcing, sometimes it is not economically feasible. An alternative might be allied nearshoring. Australia and Canada, two strong allies of the United States, could potentially provide economically feasible alternatives for sourcing certain hypersonic materials. With large deposits of cobalt and rare earth elements, both countries provide an important alternative to China (U.S. Geological Survey, 2022a).

Another place where international markets could play an important role in strengthening hypersonics supply chains is expanding the carbon fiber industry. According to a Bureau of Industry and Security (BIS) report, many companies want help from the U.S. government to identify global export opportunities (U.S. Department of Commerce, 2015). As highlighted in the Critical Raw Materials and Goods section, with the tremendous increase in demand for carbon fiber, the supplier base needs to grow and expand.

Hypersonics Challenges of the Current Export Control Regime

A constant theme throughout the working group discussions is the challenge that the current export control regime poses to international collaboration, and especially efforts to strengthen hypersonics supply chains. Export controls in the United States exist to protect American technological advantage and ensure U.S. national security. The International Traffic in Arms Regulations (ITAR) are administered to regulate the export of defense products, including a range of products from munitions to software to technical data and includes many components in the hypersonics supply chains. According to several working group participants, the fear of ITAR violations forces U.S. companies to seek domestic suppliers for the manufacturing of parts rather than pursue the export licenses required for foreign suppliers. These licenses can be especially difficult to obtain for allied nations whose privacy laws protect employees from mandated passport submission. In the U.K., for example, labor laws permit firms to hire across Europe. While U.K. companies may explicitly not recruit from specific countries outside of the E.U., meeting the U.S. requirements for workforce verification poses a challenge. University partners outside of the United States face similar challenges as most programs tend to include disproportionately more foreign nationals. While universities have some procedures in place to safeguard access to protected information, the United States can still choose to deny export licenses if there is any concern of information leakage. While certain levels of export control are important to safeguard U.S. national security, some changes could be adopted to better facilitate international partnership on hypersonics.

Similarly, foreign companies are concerned about potentially losing control of their technology due to legal agreements that give first or sole rights to the U.S. government in government-funded development projects that result in intellectual property. Companies often take a protectionist approach by turning their focus to acquiring patents in order to protect their sensitive information. Finally, in addition to strict U.S. export regulations, the language in some DoD defense acquisition contracts can be uninviting to allied nations. Contracts typically include prohibitions against foreign participation, requiring materials and subcomponents to be sourced domestically—usually without exception. There is often a requirement for programs to be U.S. in origin and performed only by U.S. citizens. Again, in certain situations, prohibition against foreign participation is appropriate for national security reasons. However, the United States should look for opportunities where international cooperation on hypersonics can be strengthened.

Summary

Overall, the U.S. currently has strong international partnerships when it comes to hypersonics. However, there are opportunities to improve upon and expand these partnerships to help strengthen hypersonics supply chains going forward.

Recommendations

- The United States should work with Australia and Canada to increase mining and processing operations for cobalt, rare earth elements, and nickel.
- The U.S. DoD should look for opportunities to increase international partnerships to address insufficient testing infrastructure.
- The U.S. Department of Defense and Australian Ministry of Defence should establish an overarching program agreement to expedite hypersonics collaboration across the board.
- Committee on Foreign Investment in the United States (CFIUS) investigations should be prioritized using a four-tiered system for organizing supply chain risk.

Conclusion

Hypersonics will likely play an increasingly critical role in the future of U.S. defense. Because of the significant advantages that hypersonic systems bring, and because of the relatively advanced state of Russian and Chinese hypersonic programs, these weapons will maintain their place in the spotlight of strategic competition. In recognition of this, it is vital that government, industry, and academia be aware of the many vulnerabilities that exist within the hypersonics supply chains. If left unaddressed, these vulnerabilities could compromise the United States' ability to effectively field hypersonic weapons. The conflict in Ukraine has demonstrated how quickly the demands of war can drain the arms inventories of supposedly well-prepared combatants. The United States must learn from this example and preempt potentially detrimental shortages.

The issues in the U.S. hypersonics supply chains have been building for years. The lack of a clear demand signal has severely impaired the future stability of the supply chain and will continue to jeopardize key national security initiatives until adequately addressed. Ultimately, it will take years of hard work before the system can rebalance and, until then, challenges will still exist. Unfortunately, there are no quick fixes. However, there are many steps government, industry, and academia can take to strengthen hypersonics supply chains for the future.

The DoD must provide a clear and constant demand signal for hypersonic systems. This, by far, is the most important step the government can take to ensure secure, healthy hypersonics supply chains. Furthermore, the DoD should request, and Congress should appropriate, reliable funding for hypersonic systems while also taking action to restore critically depleted stockpiles of strategic materials. The DoD must also pursue expanded cooperation with allies and partners, many of which can help to secure supplies of critical resources and to develop reliable and much-needed testing infrastructure. America's allies and partners are perhaps its greatest asset and one which its competitors almost universally lack. Failing to take advantage of this enormous resource would be an inexcusable blow to U.S. national security objectives.

For industry, there are numerous opportunities for growth and investment. From using additive manufacturing and digital engineering to cut costs, to increasing awareness of counterintelligence threats, to investing in new mines and carbon fiber production facilities, industry can begin today to secure supply chains for tomorrow. Considering these opportunities, industry needs a large, well-equipped workforce to fuel its innovation. Academia is crucial for educating the hypersonic workforce of the future and can also contribute to expanding testing infrastructure.

Partnerships between government, industry, and academia provide the greatest potential for overcoming the vulnerabilities of the hypersonics supply chain. However, action must be taken today. Each of these changes will take time but are crucial to securing hypersonics supply chains for years to come.

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